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## 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements

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# Fire Technology

## 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements

--Manuscript Draft--

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Abstract:	<p>Large-scale urban conflagrations in informal settlements are a frequent global event, however there is a lack of experimental research and knowledge within literature on how informal settlements fires spread to support local or national intervention strategies. This paper, therefore, presents results and analysis of a full-scale fire spread experiment of a mock 20 dwelling test settlement with a 4 by 5 layout aimed at understanding settlement-scale fire spread behaviour. A “fire line” scenario was created by simultaneously igniting four dwellings in a row, and then allowing the fire to propagate through the settlement to replicate fire disasters involving large numbers of homes. Results highlight the critical hazard posed by the close proximity of neighbouring dwellings (1-2 m), with wind playing a primary role in directing and driving the spread process. Even with a relatively mild wind speed of 15-25 km/h, the fire spread through the entire mock settlement within a mere 5 minutes. Following ignition of a given dwelling, flashover is reached very quickly, with the temperatures reaching more than 1000°C within one minute, and downwind neighbour structures igniting less than a minute thereafter. The results suggest that multi-dwelling effects are not dominant in these types of fires, but may become meaningful at a larger scale when branding and topography play a role. Findings show that on a global scale fire behaviour is analogous to a wildfire with a continuous fire front moving through an area, although individual dwellings still do follow the distinct phases of enclosure fires,</p>	

	except that collapse occurs more rapidly than in formal structures. This experiment represents one of the larger urban fire tests conducted to date, and the largest informal settlement fire experiment.
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## **Detail of revisions and responses to reviewers' comments for Article: FIRE-D-19-00231: 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements**

Note: Original reviewer comments are noted in [blue script](#), replies in *italics*. Unless stated otherwise, line numbers refer to the new version of the manuscript.

### Response to comments from Reviewer 1:

[1.1] The paper has excellent quality and touches a vital topic. It is often the poorest of us who face the highest risks of fires, and I admire the authors' dedication to protect them. I do not have any significant comments on the paper and would recommend publishing it as is. I would like however like to put some comments that came to my mind when reviewing this work for authors consideration in future.

*Thank you for the encouraging comments!*

[1.2] As the study presents a strong influence of the wind on the spread, I would recommend reporting wind conditions in more details. The height at which the wind was measured is very important, as it will be necessary to form a representative wind profile for numerical modelling of this experiment. The distinction between mean wind velocity and gusts could also be helpful to model the wind. Similarly, the terrain roughness in the proximity of the experiment would be valuable. From the drone footage, I assume the experiment was performed in the open terrain, but a topographic map of experiment surroundings would be helpful to understand this situation.

*Adding an additional figure is not really justified, as we already have quite a number of figures. Instead, we have added the coordinates of the location to the text, so that readers can readily find it on Google Earth, and also supplemented our description of the terrain with the salient information on the surroundings.*

[1.3] The wind acceleration downwind is interesting. Were you able to capture the temperature of the air at the location of the measurements?

*Unfortunately not, but it would be something to keep in mind for future experiments.*

[1.4] I also imagine that in your future research, you may want to scale the experiment up (or maybe model larger settlement configurations). I would like to point your attention to the fact that in extremally larger fires the ambient wind effects may be different than in the scale reported here. As the size of the burning area increases, the fire may cause it's own wind conditions (buoyant plume forcing airflow from all directions). Such events are often referred to as firestorms or mass conflagrations, and some aspects of this phenomena were recently reviewed in the wind and fire review paper in Fire Technology



(<https://link.springer.com/article/10.1007/s10694-018-0748-5>). The most known of such conflagrations was the fire of Tokyo in 1923 (also known as great Kanto fire, <https://www.sciencedirect.com/science/article/pii/S0167610518304975>). If the conditions for the occurrence of a firestorm are met, the ambient wind conditions will probably stop being as important, and the firestorm may drive "itself". Such large urban and suburban fires were quite well researched in the '70s, connected to possible outcomes of a nuclear attack. A good review of this research is available in (<https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nistir89-4049.pdf>). I mention this because of the intensity of the fire and the fire spread velocity you report. I can imagine that in a very large settlement the spread rate reported could lead to the emergence of some form of a firestorm, that would be the most devastating for the community of an informal settlement.

*Thank you for the very useful insights and references. We have amended our discussion of the wind effects to include reference to the large-scale effects the reviewer mention (final paragraph in the discussion).*

*Regarding the scale of the experiment, as costs become prohibitive with larger full scale experiments, we are systematically exploring how best to perform scaled down experiments with specific questions in mind.*

#### Response to comments from Reviewer 2:

Thanks for the manuscript and here are my comments;

**[2.1]** Mark the North in Figure 4. The orientations of Figure 1 and Figure 4 are different, and it would be better to rotate one of these to match.

*It is not really practical to rotate the drone images. However, to aid in orientating between Figures 1 and 4, we added the North arrow to Figure 4.*

**[2.2]** The term, "Heat flux": please indicate clearly what heat flux means: net heat flux, incident radiant heat flux, etc.

*TSCs measure the incident radiant heat flux. The text in Section 3.2 has been amended to include this information.*

**[2.3]** P.2, 59-60: FDS may not be practical at the moment due to lack of our knowledge in terms of fuel characteristics, not by computational cost. a few tens of storey buildings are modelled nowadays.

*It is agreed that single analyses could be conducted. However, as we mention in the manuscript, fuel loads in informal settlements are very diverse and variable,*

*meaningfully treating this variability in FDS simulations will require many large simulations, which are generally not practical. Few academic research outfits have access to the kind of resources required to model “tens of storey buildings” in a way that is meaningful for research. We therefore feel that our statement is correct and does not need to be amended.*

**[2.4] p.5, 2-7: any further discussion on the results influenced by this arrangement?**

*Please refer to our response to Comment 3.5 below.*

**[2.5] p.6, 2: the cardboard has been discussed earlier in the document? Please explain more about the fuel contents in the compartment.**

*Details on the fuel load are discussed in depth in Section 2.5, which follows shortly after this note. Reference to it has now been added to the statement in question.*

**[2.6] p.8, 18-21: the ignition location is outside or inside the compartment? Please add more details in terms of ignition.**

*Inside the dwellings. The statement has been amended to include this information.*

**[2.7] p.9, 37-40: is 800 C from the comparison between the visual observation and Temp data?**

*“Flashover” is often taken as 600 C, i.e. as an arbitrary cut-off temperature, although this is done in reference to an event, rather than to a process extending over a range of temperatures. In our analysis we have assumed the latter definition of flashover, i.e. as a process. In this spirit, the value of 800 C was chosen as the upper bound of the interval over which flashover happens, by inspection of the time derivative traces of the temperature measurements, and the reasons for the choice are briefly noted in the text. It is somewhat arbitrary, although the choice of cut-off value has very little effect on the results, given the extremely rapid rise in temperatures observed in all the dwellings. Using a different value would make at most a difference of a few seconds.*

**[2.8] P.11, 32-34: what type of anemometer was used?**

*We have now added this detail to the instrumentation section where the placement of the anemometers are discussed (Section 2.4).*

**[2.9] P.12, 6: "but see the results of upwind fire first." I don't really get what you mean by this. Clarify this.**

*The highest thermocouples detect the rising plume from the upwind fire first. We have revised the sentence to be clearer on this.*

[2.10] p.14, 45-52: can you elaborate this? There are four figures in Figure 7 and it is not clear what to look at.

*The text in question has been supplemented to clarify what to look at.*

[2.11] p. 16, second paragraph seems not really relevant to what has been discussed.

*We believe that this paragraph is relevant, as it stresses the limitations of the work we have done in the context of factors that were not considered and assumptions that had to be made, and also points the way to future work. We have therefore chosen to leave it unchanged.*

#### Response to comments from Reviewer 3:

Reviewer 3: This manuscript is about a large-scale experiment on fire spread through structures and a layout representative of informal settlements. It is a great contribution to the topic of fire spread in such settlements and it provides much-needed large-scale experimental data. I am definitely convinced that this work deserves to be published and the following comments are on minor aspects that I hope will help to improve the final paper.

*Thank you for the supporting and constructive comments!*

[3.1] I think that the comment on the temperature of the dwellings after flashover found in the abstract is unnecessary because it is a typical post-flashover temperature.

*The point of the comment to which the reviewer refers is not so much the temperature, as the fact that it is reached extremely quickly, which is very different from typical enclosure fire behaviour.*

[3.2] Page 2, paragraph starting at line 35: I think that some references to other fields which relate to this work are missing, such as fire spread studies in post-earthquake fires or through heterogeneous fuels in wildfires. Some fire spread mechanisms that have been described and even some design recommendations that have been proposed could help inform the research on informal settlements as there are more developed bodies of knowledge in the aforementioned fields.

*This comment is similar to Comment 1.4 raised by Reviewer 1. We have added text making reference to these other fields and sources to the text (see second paragraph of the Introduction, and the final paragraph of the Discussion section).*

[3.3] Page 2, paragraph starting at line 56 (and continuing on the next page): This paragraph deserves more explanations. Even if scaling is not perfect and simulations are difficult, I do not think that they should be discarded that easily. In the two fields of post-earthquake fires and wildland fires, they have proved to be invaluable. However, I fully agree with the authors that full-scale experiments are necessary but they cannot practically be used to solve every configuration and problem linked to informal settlements. All three approaches should be used in conjunction and in a complementary way.

*As mentioned in our response to Comment 1.4 above, we are starting to explore ways of meaningfully doing scaled experiments of informal settlement fires, although it is still early days. We amended the paragraph in question to clarify the roles of full vs reduced scale experiments.*

[3.4] Page 3, sentence between lines 21 and 28: I am not sure about this statement and it ties back to my earlier comment. I think that scaled-down experiments and simulations can help capture and detail those effects.

*Reference here is not to the scale of the experiment, but to the scale of the spreading effect. Whether via a full scale experiment or via a scaled down one, multiple dwellings are needed to represent the effect in question.*

[3.5] Page 4, line 27: In the meantime, the design decreased the lateral effects. Are windows and doors on the side of the dwellings absent in informal settlements?

*This is true. The lack of openings in the lateral direction may have favoured spread in a preferred direction, had the wind not been as unidirectional and strong as has had been during the experiment. A statement to clarify this was added at the referenced location.*

[3.6] Page 6, lines 2-7: I am wondering about the exposed cardboard. Is it representative of dwellings in informal settlements? Because this is a factor that will substantially enough dwelling-to-dwelling fire spread.

*Very much so. This is discussed at some length in our earlier work, where the choices of fuel and cardboard are developed and motivated. Please refer to the work of Cicione et al, 2019.*

[3.7] Page 9, line 39: I cannot really see the slowing down related to the 800°C value. Can the authors point out to specific curves?

*It is not slowing down to 800 C, rather 800 C is the temperature where the rate of rise starts to slow, i.e. the gradient decreases.*

[3.8] Page 10, lines 32-37: Is the A4 burning dynamics due to wind effects?

*It is not likely that wind played a role here. As clarified in our reply to Comment 2.6 of Reviewer 2, fires were ignited inside the dwelling; we simply speculated regarding the reasons for the delay in A4 reaching flashover.*

[3.9] Page 10, line 51: Explain "spread mechanisms."

*We meant to refer to fire spread events / instances, and "mechanisms" was a mis-statement. The sentence has been revised to reflect the intended meaning.*

[3.10] Page 11, lines 10-16: I understand that the experiment had a simplified fuel layout. Then, should we expect a lower rate of spread? If yes, why is the rate of spread comparable to other experiments (first paragraph of Discussion section)? Can it be attributed to the specific design chosen for this experiment?

*Our earlier work showed that the fuel load is not an important factor in the rate of spread, rather the size and proximity of dwellings, flammability of cladding, and the speed with which they reach flashover. See Cicione et al., 2019.*

[3.11] Page 11, line 35: correct "of affected." Also, I agree that this effect will need to be investigated more but more details should be provided about the anemometers, mainly their type (cup, sonic...), their exact location and their height, as the height has a lot of influence on the measured flow. The temperature has also a large influence on the flow measurements for sonic anemometers.

*Typing error "of affected" has been changed to "or affected". Regarding instrumentation, please refer to replies to previous reviewer Comments 1.4 and 2.8 on the anemometer types/locations etc.*

[3.12] I do not understand the last sentence of page 11 (lines 55-60).

*The sentence has now been amended to be more accurate and to the point.*

[3.13] Page 12, lines 4-7: Develop "see the results of upwind fire first." Why?

*Please refer to our response to the Comment 2.9 above, which deals with the same sentence.*

[3.14] Page 12, lines 14-24: I am wondering if this already has design implications or if the authors think that it is too early to draw any conclusions.

*A number of issues with potential implications as preventative measures to be implemented in informal settlements emerge from the manuscript, and we mention these in the discussion. "Design" might be somewhat too strongly phrased, but we*

*added mention of the importance of areas directly facing openings on adjacent structures to the text (second paragraph of Discussion).*

**[3.15]** Page 12, lines 27-30: Why? Is it due to the cardboard lining?

*Yes. This is already noted in the 3<sup>rd</sup> paragraph of the Discussion.*

**[3.16]** Page 13, lines 12-14: what does "ignoring the last row of dwellings" mean?

*It is not sensible to include the width of the last row of dwellings in the length over which the fire spreads.*

**[3.17]** Page 13, lines 26-32: Is there a specific reason for discarding convection in the absence of flame contact? I.e. hot gases which are not combustion gases?

*This mechanism might play a role, our analysis of the TSC data suggests that it does not play a large role, and it is generally likely to be dominated by radiative transport at these high temperatures.*

**[3.18]** Page 13, line 55: Change "thick medium" into "thermally-thick."

*Done, thank you.*

**[3.19]** Page 14, lines 1-5: same comment as before about convection without flame contact.

*Refer to reply to Comment 3.17*

**[3.20]** Page 14, lines 30-35: I think the spatial distribution of the fuel should also be mentioned.

*We amended the sentence to include spatial distribution.*

**[3.21]** Page 14, lines 38-52: This effect is very interesting. Even if the temperature in C3 shows a drastic drop, drops seem to appear almost everywhere. What about the first and second rows (1 and 4 dwellings) where it seems to happen too while one would expect less constraints on the flow?

*Drops in temperature at essentially the same time in other dwellings support our point, we simply point out C3 as it is very clear. Obviously changes in temperature at other time points cannot be correlated to this event directly.*

**[3.22]** Last word of page 14 (line 60): Change "or" into "and."

*This change is no longer relevant, as we already changed this sentence in response to Comment 1.4.*

# 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements

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# 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements

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## Abstract

Large-scale urban conflagrations in informal settlements are a frequent global event, however there is a lack of experimental research and knowledge within literature on how informal settlements fires spread to support local or national intervention strategies. This paper, therefore, presents results and analysis of a full-scale fire spread experiment of a mock 20 dwelling test settlement with a 4 by 5 layout aimed at understanding settlement-scale fire spread behaviour. A “fire line” scenario was created by simultaneously igniting four dwellings in a row, and then allowing the fire to propagate through the settlement to replicate fire disasters involving large numbers of homes. Results highlight the critical hazard posed by the close proximity of neighbouring dwellings (1-2 m), with wind playing a primary role in directing and driving the spread process. Even with a relatively mild wind speed of 15-25 km/h, the fire spread through the entire mock settlement within a mere 5 minutes. Following ignition of a given dwelling, flashover is reached very quickly, with the temperatures reaching more than 1000°C within one minute, and downwind neighbour structures igniting less than a minute thereafter. The results suggest that multi-dwelling effects are not dominant in these types of fires, but may become meaningful at a larger scale when branding and topography play a role. Findings show that on a global scale fire behaviour is analogous to a wildfire with a continuous fire front moving through an area, although individual dwellings still do follow the distinct phases of enclosure fires, except that collapse occurs more rapidly than in formal structures. This experiment represents one of the larger urban fire tests conducted to date, and the largest informal settlement fire experiment.



## 1 Introduction

Fire is an important source of light and heat in informal settlement dwellings (ISDs), but this ubiquity together with flammable construction materials and the close proximity of neighbouring structures makes these settlements especially vulnerable to disasters related to large, fast spreading fires. A single fire event in the Imizamo Yethu settlement in Cape Town (March 2017) had an estimated cost implication of around \$10 million for the city, and left almost 10,000 people homeless [1]. Informal settlement dwellings (ISDs) are homes assembled from cheap/easily scavenged materials, with limited application of standardised building codes for structural and fire safety compliance.

Municipal ordinance and building regulations developed partly in response to conflagrations in built-up areas, and have been very effective in reducing fire risk in large cities [2]. Societal knowledge on these effects developed to a large extent in response to large conflagrations experienced in the past [3, 4]. The absence of, and restricted abilities to implement, such measures in informal and semi-formal settlements is one of the primary causes of the scale and frequency of destructive informal settlement fires. With this traditional means of preventing large fires unavailable, alternative, versatile strategies of mitigating the problem need to be explored.

Critical to such an endeavour is a better understanding of the primary factors that drive fire spread at the urban scale. Included among these factors is the combination of dominant spread mechanisms such as flame impingement and radiative heat transfer with environmental factors such as wind and topography [5]. Such insight would in turn inform better judgement of which interventions are worth pursuing, while also serving as quantitative case studies to calibrate computational studies, such as stochastic spread simulations, that aim to identify areas of particularly high risk before a fire occurs [1, 6–8]. Some interventions, such as the compartmentation of settlements into zones or the use of various fire resistant materials for homes, require an understanding of fire exposure conditions and spread mechanisms to be able to evaluate whether they will improve the situation, or not.

As a phenomenon, fire does not scale well to smaller model sizes [9, 10] meaning that full-scale test are typically required. While experiments can be done using scaled down geometries, full-scale

experiments are necessary as reference and to guide the critical parameter choices that are unavoidable [11, 12]. Multi-dwelling fire dynamics simulations are also not practical, as they require significant computational effort [13, 14]. By providing a means of direct observation and measurement, as well as serving as critical benchmarks for numerical simulations, full scale fire experiments are critical if significant advances in understanding fire spread in informal settlements are to be made. Although this work has been developed to provide insight into informal settlement fire behaviour, it still provides useful data for the development of urban fire spread models as it represents one of the larger fire experiments conducted to date.

A series of foregoing studies have established a research framework within which to consider the informal settlement fire problem [1, 7, 15]. An effective standardized informal settlement dwelling fire test [7] has provided a deeper understanding of the fire dynamics associated with single dwellings. Spread to adjacent dwellings was considered in terms of direct impingement in a set of experiments involving a line of three dwellings [1]. Possible larger scale effects, including multiple spread paths and feedback mechanisms [16] can only be captured by experiments involving multiple dwellings burning at the same time, thereby prompting this work which seeks to build upon the aforementioned studies.

This paper details the results of a fire spread experiment involving 20 full-scale informal settlement dwellings. The study was conducted in an effort to (a) obtain quantitative data on the rates, temperatures, and heat flux values associated with fire-spread in a full-scale settlement, and (b) identify the mechanism by which fire spreads from dwelling to dwelling in the context of a large number of burning structures.

A compilation of the salient video footage of the experiment is available online at <https://www.youtube.com/watch?v=kkXr6ueakAU>. This video provides drone footage, side views and a number of images in excess of that presented below to assist in illustrating spread behavior beyond that which can be depicted in a paper.

## 2 Experimental Setup

### 2.1 Test site

The experiment was conducted on municipal grounds outside Worcester, South Africa, during the week of 19-23 November, 2018. The facility, which falls under the jurisdiction of the Breede Valley Fire Department, is a flat field inside an old motor racing track (33°39'23.0"S 19°24'36.9"E), which itself is located on the floodplains of the Breede River with minimal vegetation and no meaningful nearby topography. Local meteorological records for November indicate a south easterly prevailing wind direction (64% likelihood), with north westerly as a secondary direction (30 % likelihood), and hot, dry conditions (<1% likelihood of rain) [17].

### 2.2 Layout

The basic layout of the mock settlement is shown in Figure 1. With the overall aim to capture the larger scale effects that occur during settlement fires, a layout was developed that is broad enough to allow for possible lateral effects, and large enough to not be dominated by the boundary effects from the edges of the layout. Such effects include the shielding obstruction to airflow that neighbouring structures would provide, as well as the reduced supply of oxygen in case surrounding structures are also on fire. Hence, the mock settlement sought to some extent to replicate fire development for dwellings in the midst of a larger settlement.

A primary consideration in the layout was to ensure that fire could spread with the wind. With two, opposing dominant wind directions in the area, the layout was designed to be roughly symmetrical, so that the decision regarding locations of initial ignition could be left until close to the burn event itself, informed by short-term weather predictions.

To facilitate unambiguous interpretation of results, the number of added complexities in the layout were kept to a minimum. All dwellings were constructed with a floor area of 3.6 m × 2.4 m (length × width) and a height of 2.2 m (Figure 2). These dimensions are typical of ISDs, and conform to the previously established standard ISD fire test standard [7], which is based on ISO-9705 specifications

[18]. Along the longer sides, dwellings were spaced 1.2 m apart, except for four instances where the spacing was 2.2 m. These distances are typical of dwelling spaces found in denser informal settlements [6, 19]. Doors or windows were located on the left hand side of each longitudinal dwelling wall, and alternated to cover door-door, window-window, window-door, and door-window facing wall configurations across transverse alleyways (Figure 1). This was done to investigate the influence of openings on fire spread, although a side effect of this choice is that fire spread along the axis of the settlement relative to in the lateral direction would be favoured. No doors or windows were installed as they would significantly complicate the analysis, although the presence of such items would potentially slow down fire spread, and results should be interpreted accordingly.

Stand-alone sheeting panels were placed at the ends of the transverse alleyways to act as barriers and mimic the airflow shielding that a larger settlement would provide (i.e. panels were placed between rows A/B, B/C, C/D and D/E at the top and bottom of Figure 1). Similar panels were not included on entrances to longitudinal alleyways (parallel to intended burn direction), to allow for visual observations of the experiment.

### *2.3 Dwelling structure and assembly*

As-built drawings for the informal dwellings used in this experiment are given in Figure 2. Dwellings had dimensions determined according to the previously established ISD fire experiments [1, 7].

Consistent with common construction techniques used in South African informal settlements, dwellings were built as simple timber frames assembled from 48×48 mm square pine sections.

Cladding was attached to these frames, also acting as the primary means of stabilization (bracing).

Openings were left to represent doors and windows on opposing corners (actual doors and windows were not fitted). All dwellings were provided with 0.5 mm galvanized steel sheeting roof panels. 14 dwellings had galvanized sheeting as side cladding as well, with the remaining 6 clad with 12 mm thick timber planks.

1 The dwelling structure implies a ventilation factor of 0.07, calculated as  $A_v\sqrt{H_v}/A_t$  [20], with  $H_v$  the  
2 area-weighted equivalent opening height (1.66 m),  $A_v$  the total opening area (2.24 m<sup>2</sup>), and  $A_t$  the total  
3 area of internal bounding surfaces (43.7 m<sup>2</sup>).  
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8 For practical reasons of constructability, timber cladding was fitted vertically and did not overlap,  
9 while steel sheets were overlapped by 2-3 flutes. This meant that a small area of cardboard was  
10 exposed to the outside through gaps between timber planks, which was not the case with sheeting-clad  
11 dwellings, and also implies marginally increased ventilation once cardboard has burned away (refer to  
12 Section 2.5 for details on the fuel load and materials).  
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19 For reasons related to security, safety, and economy, dwelling structures were designed specifically for  
20 speed of assembly. Panels for the entire experimental settlement were pre-assembled from pre-cut  
21 timber and sheeting in a municipal warehouse, after which they were transported to the test site and  
22 erected within a single day. Two further days were necessary to furnish the dwellings with inner  
23 cardboard lining and timber cribs as fuel load, and to install instrumentation, as discussed in the  
24 following subsections.  
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## 33 *2.4 Instrumentation*

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35 The locations of sensors installed for the experiment are shown in Figure 1 and Figure 2. Inconel  
36 sheathed K-type thermocouples (1.5 mm diameter tip) and thin-skin calorimeters (TSC) manufactured  
37 following [21] were the primary sensors used. TSCs were calibrated and validated against a water-  
38 cooled heat flux gauge, providing heat flux measurements to within 10% accuracy, with a measuring  
39 range up to 200 kW/m<sup>2</sup> [1]. Thermocouples are certified to be accurate to within 0.75% by the  
40 supplier. Temperature values were logged at 10 values per minute, i.e. every 6 seconds.  
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52 Instruments were fitted into pre-assembled units, which were attached to the dwellings (Figure 2 &  
53 Figure 3) to face in the direction of the oncoming fire (two modules per dwelling, except in row A,  
54 where the fire was initiated). The positions of the instrumentation units on the dwellings are indicated  
55 in Figure 2. Instrumentation units were also attached to the edges of selected side panels (Figure 1).  
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Standard units had two thermocouple-TSC pairs at 1 m and 2 m above the ground, respectively; six units were extended to reach 2 m above the roof of the dwelling (Figure 3(a)), with two additional instrument pairs at 3 m and 4 m above the ground. In addition, each dwelling was fitted with two thermocouples measuring gas temperatures at about 5 cm below the ceiling, placed approximately 50 cm apart in the centre of the dwelling.

Instrumentation modules were assembled from 100×100 mm galvanized cold formed open square sections, generally sold in South Africa for use as rainwater gutters. Thermocouple wiring for each instrument was rolled into fire resistant mineral wool blanket and tucked inside the square sections, which led into ~50 cm deep trenches running from the base of each tree out of the settlement to the computer logging station along the transverse alleyways. Thermocouple extension wires buried in the trenches were also covered with mineral wool prior to replacing the soil.

Three hemispherical cup-type anemometers were stationed about 20 m from the settlement (Figure 1), in each case 1.6 m off the ground and with as little exposure to obstruction as possible. One was placed upwind of the settlement, one downwind, and one to the side as a reference station.

Finally, a remote controlled drone provided video footage of the fire from a safe height overhead. This footage was used to track and confirm the main events of the experiment, to identify times of collapse of each dwelling, and as a source of qualitative data on the mechanisms by which fire spread from dwelling to dwelling. This data is presented in the online video introduced previously.

## 2.5 Fuel load

Following on the standard shack-fire test developed by [7], each dwelling was fitted with a representative fire-load consisting of cardboard lining of the inner walls and 6 regularly stacked timber cribs (Figure 3(b)). Surveys have shown that South African informal dwellings have contents covering a range of fuel loads between 370 MJ/m<sup>2</sup> to 3000 MJ/m<sup>2</sup> [6]. Dwellings are typically insulated using cardboard linings on the inner walls [7]. A relatively low target fuel load of 450 MJ/m<sup>2</sup> was chosen for the current experiment, as higher fuel loads have been shown only to affect the

duration of the fire, not the initial development or spread [1] (the calculated ventilation factor 0.07 indicates dwellings in the current experiment to be ventilation controlled).

1.0 m lengths of the same 48×48 mm timber used in constructing the dwelling frames were also used as the primary fuel load, arranged into 6 cribs per dwelling, each stacked as 7 alternating layers of 4 lengths. Timber was kiln dried the week before delivery to site, with 6 samples analysed in bomb calorimeter tests yielding mean density of 520 kg/m<sup>3</sup>, heat of combustion of 16.8 MJ/kg, and water content of 5.4 wt%. These values imply an actual mean fuel load of 392 MJ/m<sup>2</sup>.

## 2.6 Burn experiment

All instruments were tested and referenced directly prior to the start of the experiment. Around noon, the burn experiment itself was started by simultaneously igniting four bundles of hessian fabric (burlap) soaked in paraffin (kerosene liquid) placed inside the dwellings at the locations shown in Figure 1.

The Breede Valley Fire Department was on site with a fire-engine and a team of fire fighters for the duration of the experiment, while a wildfire spotting team was stationed down-wind of the site, in case branding caused ignition of the surrounding brush. Fortunately, no intervention was necessary, and the experiment was allowed to run to completion.

### 3 Results

#### 3.1 Fire spread observations

A series of snapshots from the drone footage is shown in Figure 4. Of especial note is (1) how swiftly the fire spreads with the wind, (2) the ~1.0 – 2.0 m flame lengths emerging from the doors and window openings, and (3) the fact that after about 5 minutes the entire test settlement is on fire. Inspection of the drone footage indicates that all ignition events occur directly from the upwind dwelling, rather than via indirect sideways ignition. Throughout the course of the experiment, wind fluctuated between 15-25 km/h from a SSW direction (Figure 5), and about 10°-20° off the primary axis of the settlement, as shown by the direction of the smoke in the drone footage.

A timeline of ignition, end of flashover, and collapse for each dwelling is shown in Figure 6. Note that to identify ignition and flashover, the time-temperature curves shown in Figure 7 are smoothed via a 3-value running average filter. Ignition is identified as the point where recorded ceiling temperatures rise above 80 °C, so that true ignition would have occurred about 10-15 seconds earlier than the recorded times; the end of flashover is identified as the point where the temperature first exceeds 800°C. The value used to identify ignition is chosen to avoid incorrectly identifying ignition from a local spurious temperature rise; flashover is not viewed as an event but as a period in which temperature rises rapidly, with 800°C representative of values where the rise starts to slow.

Ceiling time-temperature data for each dwelling are reported in Figure 7. Curves indicate that dwellings reach the end-of-flashover very quickly after ignition and sustain a fully developed fire state at about 1100°C thereafter. Temperatures recorded above roof level (on 4 m instrument units) indicate the rising plume of the burning up-wind neighbour is first seen by the uppermost thermocouple, with smoke temperatures of 400-600°C. This indicates that such dwellings are almost at the fully developed stage and flames would be emerging from openings.

The simple numerical definitions for identifying ignition and flashover were necessary due to the difficulty associated with visually assessing fire behaviour. Calculated ignition and flashover times



would vary slightly if different criteria or temperature signatures were used. Furthermore, because of the close spacing of dwellings and the small dwelling sizes, the possibility exists of spuriously relating air temperatures associated with a burning neighbouring dwelling to the dwelling where a thermocouple is mounted, and subsequently mis-identifying the ignition time. However, as such influences will fluctuate significantly, the running average filter applied in identifying ignition can be expected to remove this effect almost entirely. Where possible the aerial footage was utilised to validate findings.

Notice in Figure 6 that around 5 minutes into the experiment, every single dwelling was fully involved. The distribution of times between ignition and the end of flashover, between end of flashover and collapse, and between end of flashover and ignition of the down-wind neighbour, is summarized in Figure 8. With the exception of dwellings in Row A where the experiment was initiated, flashover was reached very quickly, within less than a minute after ignition of the dwelling. Of all the dwellings, nine experienced time from ignition as defined above to end of flashover of  $1\frac{1}{4}$  minutes or less, seven at  $1\frac{1}{2}$  minutes, and only three dwellings required longer than this (note that dwelling D4 was not included due to equipment malfunction). Dwelling A4 took longer than the other ignited dwellings to reach flashover, presumably due to flames within the dwelling not impinging on cardboard as quickly as dwellings A1-A3. As seen in previous experiments [1] the time to flashover closely correlates to the full ignition of the cardboard insulation.

Timber-clad dwellings collapsed soon after the start of the fully developed phase as a result of lost bracing shown by 5 dwellings collapsing in around  $2\frac{1}{2}$  minutes, whilst the final one (B1) required around  $3\frac{3}{4}$  minutes. From Figure 8 the ignition of the down-wind neighbour occurs within less than a minute of the end of flashover, with 2 dwellings downwind igniting even before the end-of-flashover criteria was achieved, with a further 8 instances of fire spread events occurring within 20 seconds, and the final 4 in under a minute. This highlights how the ignition and development stages up to flashover are critical for predicting fire spread. The total fuel load within a dwelling is of less importance compared to how easily items can catch fire and how fast ignition transitions to flashover.

Figure 9 shows a number of photos taken during the experiment. Of especial note is (a) the presence of flame impingement as a likely fire spread mechanism, and (b) flame lengths extending 2.5 – 3 m above the dwellings during the fully developed stage. The equipment trees which were 4 m tall were fully engulfed in flames, and flame lengths that would cross typical settlement pathways easily occurred. Dwellings are often not well sealed, and in many instances have combustible material such as newspaper compacted and pushed into openings to prevent drafts, meaning that they would readily ignite when exposed to flame impingement; in this experiment the flames emerging from the on-fire dwellings would impinge onto a wall, rather than onto/through an opening.

Recordings of wind speed with time are compared for the three anemometers in Figure 5. Note the contrast in the readings before initial ignition of the experiment versus once the fire has spread into the settlement. Readings follow one another closely prior to ignition, but as the fire reaches full intensity the downwind recorded wind speeds are notably higher than the upwind and reference values. This effect requires more research and experimentation, as it is not necessarily the same phenomena as observed in wildland fires, although the scale of such experiments is much larger so it is difficult to make direct comparisons. This effect may have been influenced by the size and geometry of the setup, or affected by the rising buoyant air from the fire.

### *3.2 Heat flux measurements*

Incident radiant heat flux values onto downwind facades facing a burning dwelling, measured via the TSCs mounted on the downwind dwelling, are shown in Figure 10 and Figure 11, with measurements on side panels shown in Figure 12. This set of heat flux values shown is representative of all dwellings for which useful heat flux values were obtained, and shows the salient behaviour most clearly. Heat flux values for all dwellings reach values of 50 – 100 kW/m<sup>2</sup> opposite vents (doors/windows) of the dwelling immediately downwind (distance of either 1.2m or 2.2m; see Figure 1), once it reaches the fully-developed fire stage. Values are only considered meaningful while they are below the calibration limit of the TSCs.

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Three notable observations emerge from the values recorded prior to flame impingement. Firstly, heat flux at the lowest TSC (1 m from the ground) is consistently the lowest of the recorded values at a given time on a given instrument unit; instruments above roof level do not record very high values, but see the temperature rise due to the plume from the upwind fire first.

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Secondly, when the cladding itself is not burning (i.e. for galvanized sheeting walls/facades) heat flux opposite doors/windows reach higher values notably sooner than values opposite the part of the wall with no vents, caused by the flames emerging from openings. In contrast heat flux opposite timber facades depends primarily on height above the ground, with only minor effects from the position of the vent. This is due to the timber cladding on walls exerting a high heat flux as it burns, potentially approaching the magnitude of the flux from the flames emerging from openings, meaning that such walls exert a more consistent flux across the entire wall area.

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Thirdly, ignition of the target dwellings occurs when the heat flux exposure is still relatively low ( $<30$  kW/m<sup>2</sup>). Higher heat flux values are seen as the upwind dwelling continues to burn, in some cases directly associated with flame impingement on the TSCs (e.g. B0, Figure 12). In such cases heat fluxes range between 100 and 250 kW/m<sup>2</sup>, with upper values consistent with observations in post-flashover enclosures. Note that the maximum heat fluxes recorded are outside of the range that instruments can be calibrated for, and results should be interpreted accordingly. Readings have been adjusted to account for convective exposure, but this may also influence instrument accuracy.

## 4 Discussion

The combination of drone footage and temperature profiles illustrate the primary role played by the wind in aiding fire spread in informal settlements. All spread events occurred in the direction of the wind, despite transverse dwelling separation being only 1 m. Multi-dwelling spread mechanisms, in which a downwind dwelling is ignited from a transverse direction rather than directly from the upwind neighbour, therefore do not appear to be significant in the presence of a mild wind. Ignoring the width of the last row of dwellings, the results imply a mean spread rate of about 3.6 m/min. This value is notably smaller than the wildfire spread rate of 20-35 m/min expected for a 17 km/h average wind speed [22], but reasonably comparable to the maximum spread rate of 2.3 m/min estimated for the Imizamu Yethu settlement fire [19], a far more complex fire spread situation which includes efforts to intervene and slow its progress.

Ignition can occur as a result of either direct flame impingement onto flammable material (cardboard or timber frames through gaps and vents; timber cladding; especially opposite vents and openings of adjacent structures), or by receiving sufficient radiation to exceed the critical heat flux of any of the materials present. Due to the large size of this experiment it is not possible to accurately measure behaviour at all positions, meaning that in some cases it is difficult to identify ignition mechanisms with absolute certainty. Photographic evidence (Figure 9) suggests that flame impingement was certainly present, and may well have been a dominant mechanism for fire spread in this experiment, although ignition by radiative exposure cannot be ruled out for all dwellings. The small dwelling spacings ( $< 2$  m) common in these settlements provide ample opportunity for direct flame impingement to spread the fire from dwelling to dwelling, with the combination of large fuel loads and small, reasonably ventilated enclosures resulting in very quick development times from ignition through flashover into fully developed stages. As a result, fires can spread into multiple dwellings extremely quickly.

Predictions for a thermally-thick medium ignition model for timber suggest that even in the absence of direct flame impingement, heat flux values of around  $25 \text{ kW/m}^2$  would result in ignition within less

than a minute [3], while the measured heat flux values around the recorded times of ignition are in excess of self-igniting heat flux values for most common household materials (8-20 kW/m<sup>2</sup> [5]). Although this suggests that radiation-induced self-ignition might be the dominant mechanism for fire spread, photographic evidence indicates that direct flame impingement was also present. Larger heat flux values likely represent direct flame impingement on the TSC disks, an observation which is confirmed for a number of the dwellings from the drone footage. Flame impingement is also supported by the observed spreading times, with no statistically significant difference in spreading rate between the 1.2 m and 2.2 m spaced dwellings visible in the overall results (Figure 8). Given the small time of spread and the proximity of dwellings, both mechanisms therefore contributed to the rapid spread observed. Dwelling spacing in typical dense informal settlements (1.0-1.5 m) are far smaller than the critical separation necessary to prevent rapid fire spread.

The observed temperature curves are consistent with the observations of Magnusson [23] for enclosures with intermediate ventilation factor values (0.07 in this case, see above). The mock dwellings in this experiment are initially well ventilated, before fires become marginally ventilation controlled and plateau around 1100°C. Of course, the uniform nature and distribution of the fuel load used in this experiment is only representative of household items in an average sense, and do not capture the effect items such as cooking oil, aerosol cans, and stored fuel would contribute [6].

It is possible that the importance of ventilation shows up as a larger-scale effect in the observed results: consider that dwelling C3 was surrounded by timber-clad dwellings on all four sides, and was the dwelling with the longest survival time. Intuitively it would be expected that C3 would experience intense fire exposure from the neighbouring timber structures and collapse rapidly. However, the intense burning of its timber-clad neighbours may have deprived its oxygen supply for a period, delaying the collapse of its timber frame structure. This hypothesis is supported by the ~350°C drop in the recorded ceiling temperature in C3 just as dwelling D3 goes into the flashover phase (green line in panel 3 of Figure 7).

Figure 5 presents the wind speed at the anemometer positions during the period of the experiment, presenting data both before and during the experiment. As would be expected in a real-life experiment the wind speed fluctuated continuously, with typical values between 10-20 km/hr, with gusts reaching around 25 km/hr. Of great interest is the wind speed at the down-wind anemometer position, which is shown to increase at around 4 minutes into the experiment, when the first 16 homes had ignited, and continues until around 23 minutes after ignition, but less markedly towards the end. This apparent accelerating effect of the fire on average wind speed down-wind of the fire has in the past been associated with wildland fire [24, 25], and could possibly affect spread rates and ignition over longer distances through branding if intensified in a larger fire. Large conflagrations are known to modify wind conditions markedly [26, 27], so that this observation may reflect a similar effect at the lower end of the size scale. In such large fires branding becomes an important means of fire-spread, although the spatial extent of the mock settlement used in the present experiment is not sufficient for the effect of branding be observed. Additional factors not accounted for in the experiment, such as topography and multi-storey structures, are also expected to affect the rate of fire spread and fire-wind interaction. This does highlight how in larger informal settlement fires, such as when hundreds of dwellings burn in a single disaster, it may be possible that fire phenomena associated with wildland fire behaviour may occur [28].

## 5 Conclusion

A full-scale fire spread experiment of a mock 20-dwelling mock settlement emphasises the critical hazard posed by the close proximity of dwellings in informal settlements. Combined with a mild wind in driving and directing the process, fire spread through the mock settlement within 5 minutes. The small dwelling spacings ( $< 2$  m) that are common in these settlements results in both direct flame impingement and radiation-induces auto ignition as the dominant mechanisms for fire spread from dwelling to dwelling, with the combination of large fuel loads and small, reasonably ventilated enclosures resulting in very quick development times from ignition through flashover into fully developed stages.

The results provide an initial set of observations against which event-based modelling of fire spread through informal settlements can be benchmarked and calibrated. However, factors resulting from human interaction with the fire, for example the effectiveness of firefighting efforts, and relocation of household items and furniture in response to an oncoming fire, will require a combination of fire dynamics and agent-based simulation techniques. Building on these observations, future experiments will be aimed specifically at (a) complicating factors such as branding, topography, multi-storey structures, and fluctuating wind, and at (b) developing potential measures of intervention that can delay the speed with which fire spread occurs.

On a macro-scale the fire spread is analogous to that observed in wildland fires, with the fire front moving progressively through combustible material. This behaviour would be aided if additional fuels were stacked between dwellings, as is often the case in real informal settlements where piles of tyres, rubbish, stored wooden pallets and broken equipment can be found. However, on an individual home level the distinct stages of enclosure fire development are recorded for dwellings. Hence, modelling of fire spread on global scale could range from between using simplified models with average spread rates defined by empirical terms that are a function of fuel type, home density, topography and wind. Alternatively, detailed computational fluid dynamics models, or one/two-zone models could be utilised to predict spread between individual dwellings, and such data used as sub-models within

global analyses considering each home individually. However, the challenge with all modelling techniques is that information about fuel load and settlement configuration is typically not known accurately, negating the potential to “accurately” calculate spread rates. Nevertheless, predictions about fire spread are still useful for potentially identifying how settlement layouts, construction types, fire safety interventions, and disaster preparedness may be improved.



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## Figure Captions:

Figure 1: Overall layout of the model settlement, also indicating instrumentation positions and positions where the experiment was initiated.

Figure 2: As-built structural drawings for dwelling frames and assembly, showing both timber-clad and galvanised sheeting-clad side panels. All dwellings had sheeting-clad roof panels. Also shown are the types of instrumentation modules and their positions on the dwelling walls.

Figure 3: (a) Thermocouples (TC) and thin-skin calorimeters (TSC) are fixed in position via modular instrumentation units pre-assembled using cold-formed steel conduits and fire-retarding blanket. Plastic wrapping was removed prior to the experiment. (b) Dwelling interior prior to burning, showing carboard linings and six timber cribs stacked from 48x48 mm 1.0 m lengths of South African pine.

Figure 4: Snapshots from overhead drone footage, starting from soon after ignition to just before the final dwelling collapse. Times are indicated relative to point of ignition.

Figure 5: Wind speed traces as recorded by the three anemometers, with time relative to the start of the fire. Note the decoupling of the windspeed down-wind from the fire to the up-wind and far-field traces as the fire reaches full intensity.

Figure 6: Summary of timeline for the experiment. Dashed line indicates timeline based only on video footage, where the thermocouples fitted to the ceiling malfunctioned.

Figure 7: Average ceiling temperatures inside each dwelling, clearly illustrating how down-wind ignition follows shortly after flashover of a given dwelling.

Figure 8: (a-c) Frequency distributions of time between salient events during the burning of individual dwellings and fire spread to down-wind neighbours. (d) Comparison of time lag between temperature

traces (represented by time between end of flashover events) for different separation distances, with error bars representing one standard deviation.

Figure 9: Photographic evidence documenting fire spread by direct flame impingement (FI), flame lengths out of dwelling vents (FL), and flame heights above roof level (FH), with 4 m tall instrument units (IU) pointed out for reference. Where times are not obtainable from the source footage, it is estimated based on correlation to other footage, and indicated as approximate (indicated with ~).

Figure 10: Heat flux recorded across a 2.2 m distance separating the 4-instrument units on dwellings C1 and C2, facing dwellings B1 and B2, respectively.

Figure 11: Heat flux recorded across a 1.2 m distance separating the 2-instrument units on dwellings B2, B3, C3, and D2, facing dwellings A2, A3, B3, and C2, respectively.

Figure 12: Heat flux onto side panels, as labelled in Figure 1. High heat flux values on B0 correspond to direct flame impingement.

# 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements

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## Abstract

Large-scale urban conflagrations in informal settlements are a frequent global event, however there is a lack of experimental research and knowledge within literature on how informal settlements fires spread to support local or national intervention strategies. This paper, therefore, presents results and analysis of a full-scale fire spread experiment of a mock 20 dwelling test settlement with a 4 by 5 layout aimed at understanding settlement-scale fire spread behaviour. A “fire line” scenario was created by simultaneously igniting four dwellings in a row, and then allowing the fire to propagate through the settlement to replicate fire disasters involving large numbers of homes. Results highlight the critical hazard posed by the close proximity of neighbouring dwellings (1-2 m), with wind playing a primary role in directing and driving the spread process. Even with a relatively mild wind speed of 15-25 km/h, the fire spread through the entire mock settlement within a mere 5 minutes. Following ignition of a given dwelling, flashover is reached very quickly, with the temperatures reaching more than 1000°C within one minute, and downwind neighbour structures igniting less than a minute thereafter. The results suggest that multi-dwelling effects are not dominant in these types of fires, but may become meaningful at a larger scale when branding and topography play a role. Findings show that on a global scale fire behaviour is analogous to a wildfire with a continuous fire front moving through an area, although individual dwellings still do follow the distinct phases of enclosure fires, except that collapse occurs more rapidly than in formal structures. This experiment represents one of the larger urban fire tests conducted to date, and the largest informal settlement fire experiment.

## 1 Introduction

Fire is an important source of light and heat in informal settlement dwellings (ISDs), but this ubiquity together with flammable construction materials and the close proximity of neighbouring structures makes these settlements especially vulnerable to disasters related to large, fast spreading fires. A single fire event in the Imizamo Yethu settlement in Cape Town (March 2017) had an estimated cost implication of around \$10 million for the city, and left almost 10,000 people homeless [1]. Informal settlement dwellings (ISDs) are homes assembled from cheap/easily scavenged materials, with limited application of standardised building codes for structural and fire safety compliance.

Municipal ordinance and building regulations developed partly in response to conflagrations in built-up areas, and have been very effective in reducing fire risk in large cities [2]. Societal knowledge on these effects developed to a large extent in response to large conflagrations experienced in the past [3, 4]. The absence of, and restricted abilities to implement, such measures in informal and semi-formal settlements is one of the primary causes of the scale and frequency of destructive informal settlement fires. With this traditional means of preventing large fires unavailable, alternative, versatile strategies of mitigating the problem need to be explored.

Critical to such an endeavour is a better understanding of the primary factors that drive fire spread at the urban scale. Included among these factors is the combination of dominant spread mechanisms such as flame impingement and radiative heat transfer with environmental factors such as wind and topography [5]. Such insight would in turn inform better judgement of which interventions are worth pursuing, while also serving as quantitative case studies to calibrate computational studies, such as stochastic spread simulations, that aim to identify areas of particularly high risk before a fire occurs [1, 6–8]. Some interventions, such as the compartmentation of settlements into zones or the use of various fire resistant materials for homes, require an understanding of fire exposure conditions and spread mechanisms to be able to evaluate whether they will improve the situation, or not.

As a phenomenon, fire does not scale well to smaller model sizes [9, 10] meaning that full-scale test are typically required. While experiments can be done using scaled down geometries, full-scale

experiments are necessary as reference and to guide the critical parameter choices that are unavoidable

[11, 12]. Multi-dwelling fire dynamics simulations are also not practical, as they require significant computational effort [13, 14]. By providing a means of direct observation and measurement, as well as serving as critical benchmarks for numerical simulations, full scale fire experiments are critical if significant advances in understanding fire spread in informal settlements are to be made. Although this work has been developed to provide insight into informal settlement fire behaviour, it still provides useful data for the development of urban fire spread models as it represents one of the larger fire experiments conducted to date.

A series of foregoing studies have established a research framework within which to consider the informal settlement fire problem [1, 7, 15]. An effective standardized informal settlement dwelling fire test [7] has provided a deeper understanding of the fire dynamics associated with single dwellings. Spread to adjacent dwellings was considered in terms of direct impingement in a set of experiments involving a line of three dwellings [1]. Possible larger scale effects, including multiple spread paths and feedback mechanisms [16] can only be captured by experiments involving multiple dwellings burning at the same time, thereby prompting this work which seeks to build upon the aforementioned studies.

This paper details the results of a fire spread experiment involving 20 full-scale informal settlement dwellings. The study was conducted in an effort to (a) obtain quantitative data on the rates, temperatures, and heat flux values associated with fire-spread in a full-scale settlement, and (b) identify the mechanism by which fire spreads from dwelling to dwelling in the context of a large number of burning structures.

A compilation of the salient video footage of the experiment is available online at <https://www.youtube.com/watch?v=kkXr6ueakAU>. This video provides drone footage, side views and a number of images in excess of that presented below to assist in illustrating spread behavior beyond that which can be depicted in a paper.



## 2 Experimental Setup

### 2.1 Test site

The experiment was conducted on municipal grounds outside Worcester, South Africa, during the week of 19-23 November, 2018. The facility, which falls under the jurisdiction of the Breede Valley Fire Department, is a flat field inside an old motor racing track ([33°39'23.0"S 19°24'36.9"E](#)), [which itself is located on the floodplains of the Breede River with minimal vegetation and no meaningful nearby topography](#). [Local m](#)Meteorological records for ~~the area in~~ November indicate a south easterly prevailing wind direction (64% likelihood), with north westerly as a secondary direction (30 % likelihood), and hot, dry conditions (<1% likelihood of rain) [17].

### 2.2 Layout

The basic layout of the mock settlement is shown in Figure 1. With the overall aim to capture the larger scale effects that occur during settlement fires, a layout was developed that is broad enough to allow for possible lateral effects, and large enough to not be dominated by the boundary effects from the edges of the layout. Such effects include the shielding obstruction to airflow that neighbouring structures would provide, as well as the reduced supply of oxygen in case surrounding structures are also on fire. Hence, the mock settlement sought to some extent to replicate fire development for dwellings in the midst of a larger settlement.

A primary consideration in the layout was to ensure that fire could spread with the wind. With two, opposing dominant wind directions in the area, the layout was designed to be roughly symmetrical, so that the decision regarding locations of initial ignition could be left until close to the burn event itself, informed by short-term weather predictions.

To facilitate unambiguous interpretation of results, the number of added complexities in the layout were kept to a minimum. All dwellings were constructed with a floor area of 3.6 m × 2.4 m (length × width) and a height of 2.2 m (Figure 2). These dimensions are typical of ISDs, and conform to the previously established standard ISD fire test standard [7], which is based on ISO-9705 specifications

[18]. Along the longer sides, dwellings were spaced 1.2 m apart, except for four instances where the spacing was 2.2 m. These distances are typical of dwelling spaces found in denser informal settlements [6, 19]. Doors or windows were located on the left hand side of each longitudinal dwelling wall, and alternated to cover door-door, window-window, window-door, and door-window facing wall configurations across transverse alleyways (Figure 1). This was done to investigate the influence of openings on fire spread, although a side effect of this choice is that fire spread along the axis of the settlement relative to in the lateral direction would be favoured. No doors or windows were installed as they would significantly complicate the analysis, although the presence of such items would potentially slow down fire spread, and results should be interpreted accordingly.

Stand-alone sheeting panels were placed at the ends of the transverse alleyways to act as barriers and mimic the airflow shielding that a larger settlement would provide (i.e. panels were placed between rows A/B, B/C, C/D and D/E at the top and bottom of Figure 1). Similar panels were not included on entrances to longitudinal alleyways (parallel to intended burn direction), to allow for visual observations of the experiment.

### *2.3 Dwelling structure and assembly*

As-built drawings for the informal dwellings used in this experiment are given in Figure 2. Dwellings had dimensions determined according to the previously established ISD fire experiments [1, 7]. Consistent with common construction techniques used in South African informal settlements, dwellings were built as simple timber frames assembled from 48×48 mm square pine sections. Cladding was attached to these frames, also acting as the primary means of stabilization (bracing). Openings were left to represent doors and windows on opposing corners (actual doors and windows were not fitted). All dwellings were provided with 0.5 mm galvanized steel sheeting roof panels. 14 dwellings had galvanized sheeting as side cladding as well, with the remaining 6 clad with 12 mm thick timber planks.

The dwelling structure implies a ventilation factor of 0.07, calculated as  $A_v\sqrt{H_v}/A_t$  [20], with  $H_v$  the area-weighted equivalent opening height (1.66 m),  $A_v$  the total opening area (2.24 m<sup>2</sup>), and  $A_t$  the total area of internal bounding surfaces (43.7 m<sup>2</sup>).

For practical reasons of constructability, timber cladding was fitted vertically and did not overlap, while steel sheets were overlapped by 2-3 flutes. This meant that a small area of cardboard was exposed to the outside through gaps between timber planks, which was not the case with sheeting-clad dwellings, and also implies marginally increased ventilation once cardboard has burned away ([refer to Section 2.5 for details on the fuel load and materials](#)).

For reasons related to security, safety, and economy, dwelling structures were designed specifically for speed of assembly. Panels for the entire experimental settlement were pre-assembled from pre-cut timber and sheeting in a municipal warehouse, after which they were transported to the test site and erected within a single day. Two further days were necessary to furnish the dwellings with inner cardboard lining and timber cribs as fuel load, and to install instrumentation, as discussed in the following subsections.

#### *2.4 Instrumentation*

The locations of sensors installed for the experiment are shown in Figure 1 and Figure 2. Inconel sheathed K-type thermocouples (1.5 mm diameter tip) and thin-skin calorimeters (TSC) manufactured following [21] were the primary sensors used. TSCs were calibrated and validated against a water-cooled heat flux gauge, providing heat flux measurements to within 10% accuracy, with a measuring range up to 200 kW/m<sup>2</sup> [1]. Thermocouples are certified to be accurate to within 0.75% by the supplier. Temperature values were logged at 10 values per minute, i.e. every 6 seconds.

Instruments were fitted into pre-assembled units, which were attached to the dwellings (Figure 2 & Figure 3) to face in the direction of the oncoming fire (two modules per dwelling, except in row A, where the fire was initiated). The positions of the instrumentation units on the dwellings are indicated in Figure 2. Instrumentation units were also attached to the edges of selected side panels (Figure 1).

Standard units had two thermocouple-TSC pairs at 1 m and 2 m above the ground, respectively; six units were extended to reach 2 m above the roof of the dwelling (Figure 3(a)), with two additional instrument pairs at 3 m and 4 m above the ground. In addition, each dwelling was fitted with two thermocouples measuring gas temperatures at about 5 cm below the ceiling, placed approximately 50 cm apart in the centre of the dwelling.

Instrumentation modules were assembled from 100×100 mm galvanized cold formed open square sections, generally sold in South Africa for use as rainwater gutters. Thermocouple wiring for each instrument was rolled into fire resistant mineral wool blanket and tucked inside the square sections, which led into ~50 cm deep trenches running from the base of each tree out of the settlement to the computer logging station along the transverse alleyways. Thermocouple extension wires buried in the trenches were also covered with mineral wool prior to replacing the soil.

Three hemispherical cup-type anemometers were stationed about 20 m from the settlement (Figure 1), in each case 1.6 m off the ground and with as little exposure to obstruction as possible. One was placed upwind of the settlement, one downwind, and one to the side as a reference station.

Finally, a remote controlled drone provided video footage of the fire from a safe height overhead. This footage was used to track and confirm the main events of the experiment, to identify times of collapse of each dwelling, and as a source of qualitative data on the mechanisms by which fire spread from dwelling to dwelling. This data is presented in the online video introduced previously.

## *2.5 Fuel load*

Following on the standard shack-fire test developed by [7], each dwelling was fitted with a representative fire-load consisting of cardboard lining of the inner walls and 6 regularly stacked timber cribs (Figure 3(b)). Surveys have shown that South African informal dwellings have contents covering a range of fuel loads between 370 MJ/m<sup>2</sup> to 3000 MJ/m<sup>2</sup> [6]. Dwellings are typically insulated using cardboard linings on the inner walls [7]. A relatively low target fuel load of 450 MJ/m<sup>2</sup> was chosen for the current experiment, as higher fuel loads have been shown only to affect the

duration of the fire, not the initial development or spread [1] (the calculated ventilation factor 0.07 indicates dwellings in the current experiment to be ventilation controlled).

1.0 m lengths of the same 48×48 mm timber used in constructing the dwelling frames were also used as the primary fuel load, arranged into 6 cribs per dwelling, each stacked as 7 alternating layers of 4 lengths. Timber was kiln dried the week before delivery to site, with 6 samples analysed in bomb calorimeter tests yielding mean density of 520 kg/m<sup>3</sup>, heat of combustion of 16.8 MJ/kg, and water content of 5.4 wt%. These values imply an actual mean fuel load of 392 MJ/m<sup>2</sup>.

## *2.6 Burn experiment*

All instruments were tested and referenced directly prior to the start of the experiment. Around noon, the burn experiment itself was started by simultaneously igniting four bundles of hessian fabric (burlap) soaked in paraffin (kerosene liquid) placed inside the dwellings at the locations shown in Figure 1.

The Breede Valley Fire Department was on site with a fire-engine and a team of fire fighters for the duration of the experiment, while a wildfire spotting team was stationed down-wind of the site, in case branding caused ignition of the surrounding brush. Fortunately, no intervention was necessary, and the experiment was allowed to run to completion.

### 3 Results

#### 3.1 Fire spread observations

A series of snapshots from the drone footage is shown in Figure 4. Of especial note is (1) how swiftly the fire spreads with the wind, (2) the ~1.0 – 2.0 m flame lengths emerging from the doors and window openings, and (3) the fact that after about 5 minutes the entire test settlement is on fire. Inspection of the drone footage indicates that all ignition events occur directly from the upwind dwelling, rather than via indirect sideways ignition. Throughout the course of the experiment, wind fluctuated between 15-25 km/h from a SSW direction (Figure 5), and about 10°-20° off the primary axis of the settlement, as shown by the direction of the smoke in the drone footage.

A timeline of ignition, end of flashover, and collapse for each dwelling is shown in Figure 6. Note that to identify ignition and flashover, the time-temperature curves shown in Figure 7 are smoothed via a 3-value running average filter. Ignition is identified as the point where recorded ceiling temperatures rise above 80 °C, so that true ignition would have occurred about 10-15 seconds earlier than the recorded times; the end of flashover is identified as the point where the temperature first exceeds 800°C. The value used to identify ignition is chosen to avoid incorrectly identifying ignition from a local spurious temperature rise; flashover is not viewed as an event but as a period in which temperature rises rapidly, with 800°C representative of values where the rise starts to slow.

Ceiling time-temperature data for each dwelling are reported in Figure 7. Curves indicate that dwellings reach the end-of-flashover very quickly after ignition and sustain a fully developed fire state at about 1100°C thereafter. Temperatures recorded above roof level (on 4 m instrument units) indicate the rising plume of the burning up-wind neighbour is first seen by the uppermost thermocouple, with smoke temperatures of 400-600°C. This indicates that such dwellings are almost at the fully developed stage and flames would be emerging from openings.

The simple numerical definitions for identifying ignition and flashover were necessary due to the difficulty associated with visually assessing fire behaviour. Calculated ignition and flashover times

would vary slightly if different criteria or temperature signatures were used. Furthermore, because of the close spacing of dwellings and the small dwelling sizes, the possibility exists of spuriously relating air temperatures associated with a burning neighbouring dwelling to the dwelling where a thermocouple is mounted, and subsequently mis-identifying the ignition time. However, as such influences will fluctuate significantly, the running average filter applied in identifying ignition can be expected to remove this effect almost entirely. Where possible the aerial footage was utilised to validate findings.

Notice in Figure 6 that around 5 minutes into the experiment, every single dwelling was fully involved. The distribution of times between ignition and the end of flashover, between end of flashover and collapse, and between end of flashover and ignition of the down-wind neighbour, is summarized in Figure 8. With the exception of dwellings in Row A where the experiment was initiated, flashover was reached very quickly, within less than a minute after ignition of the dwelling. Of all the dwellings, nine experienced time from ignition as defined above to end of flashover of  $1\frac{1}{4}$  minutes or less, seven at  $1\frac{1}{2}$  minutes, and only three dwellings required longer than this (note that dwelling D4 was not included due to equipment malfunction). Dwelling A4 took longer than the other ignited dwellings to reach flashover, presumably due to flames within the dwelling not impinging on cardboard as quickly as dwellings A1-A3. As seen in previous experiments [1] the time to flashover closely correlates to the full ignition of the cardboard insulation.

Timber-clad dwellings collapsed soon after the start of the fully developed phase as a result of lost bracing shown by 5 dwellings collapsing in around  $2\frac{1}{2}$  minutes, whilst the final one (B1) required around  $3\frac{3}{4}$  minutes. From Figure 8 the ignition of the down-wind neighbour occurs within less than a minute of the end of flashover, with 2 dwellings downwind igniting even before the end-of-flashover criteria was achieved, with a further 8 instances of fire spread ~~mechanisms-events~~ occurring within 20 seconds, and the final 4 in under a minute. This highlights how the ignition and development stages up to flashover are critical for predicting fire spread. The total fuel load within a dwelling is of less importance compared to how easily items can catch fire and how fast ignition transitions to flashover.

Figure 9 shows a number of photos taken during the experiment. Of especial note is (a) the presence of flame impingement as a likely fire spread mechanism, and (b) flame lengths extending 2.5 – 3 m above the dwellings during the fully developed stage. The equipment trees which were 4 m tall were fully engulfed in flames, and flame lengths that would cross typical settlement pathways easily occurred. Dwellings are often not well sealed, and in many instances have combustible material such as newspaper compacted and pushed into openings to prevent drafts, meaning that they would readily ignite when exposed to flame impingement; in this experiment the flames emerging from the on-fire dwellings would impinge onto a wall, rather than onto/through an opening.

Recordings of wind speed with time are compared for the three anemometers in Figure 5. Note the contrast in the readings before initial ignition of the experiment versus once the fire has spread into the settlement. Readings follow one another closely prior to ignition, but as the fire reaches full intensity the downwind recorded wind speeds are notably higher than the upwind and reference values. This effect requires more research and experimentation, as it is not necessarily the same phenomena as observed in wildland fires, although the scale of such experiments is much larger so it is difficult to make direct comparisons. This effect may have been influenced by the size and geometry of the setup, ~~or~~ affected by the rising buoyant air from the fire.

### 3.2 Heat flux measurements

Incident radiant ~~Heat-heat~~ flux values onto downwind facades facing a burning dwelling, measured via the TSCs mounted on the downwind dwelling, are shown in Figure 10 and Figure 11, with measurements on side panels shown in Figure 12. This set of heat flux values shown is representative of all dwellings for which useful heat flux values were obtained, and shows the salient behaviour most clearly. Heat flux values for all dwellings reach values of 50 – 100 kW/m<sup>2</sup> opposite vents (doors/windows) of the dwelling immediately downwind (distance of either 1.2m or 2.2m; see Figure 1), once it reaches the fully-developed fire stage. Values are only considered ~~up-meaningful while they are below~~ up-meaningful while they are below ~~to the time when the dwelling upon which the TSCs are mounted reaches end-of-flashover criteria, or starts recording values above~~ the calibration limit of the TSCs.



Three notable observations emerge from the values recorded prior to flame impingement. Firstly, heat flux at the lowest TSC (1 m from the ground) is consistently the lowest of the recorded values at a given time on a given instrument unit; instruments above roof level do not record very high values, but see the ~~results~~ temperature rise due to the plume from the ~~of~~ upwind fire first.

Secondly, when the cladding itself is not burning (i.e. for galvanized sheeting walls/facades) heat flux opposite doors/windows reach higher values notably sooner than values opposite the part of the wall with no vents, caused by the flames emerging from openings. In contrast heat flux opposite timber facades depends primarily on height above the ground, with only minor effects from the position of the vent. This is due to the timber cladding on walls exerting a high heat flux as it burns, potentially approaching the magnitude of the flux from the flames emerging from openings, meaning that such walls exert a more consistent flux across the entire wall area.

Thirdly, ignition of the target dwellings occurs when the heat flux exposure is still relatively low ( $<30$  kW/m<sup>2</sup>). Higher heat flux values are seen as the upwind dwelling continues to burn, in some cases directly associated with flame impingement on the TSCs (e.g. B0, Figure 12). In such cases heat fluxes range between 100 and 250 kW/m<sup>2</sup>, with upper values consistent with observations in post-flashover enclosures. Note that the maximum heat fluxes recorded are outside of the range that instruments can be calibrated for, and results should be interpreted accordingly. Readings have been adjusted to account for convective exposure, but this may also influence instrument accuracy.

## 4 Discussion

The combination of drone footage and temperature profiles illustrate the primary role played by the wind in aiding fire spread in informal settlements. All spread events occurred in the direction of the wind, despite transverse dwelling separation being only 1 m. Multi-dwelling spread mechanisms, in which a downwind dwelling is ignited from a transverse direction rather than directly from the upwind neighbour, therefore do not appear to be significant in the presence of a mild wind. Ignoring the width of the last row of dwellings, the results imply a mean spread rate of about 3.6 m/min. This value is notably smaller than the wildfire spread rate of 20-35 m/min expected for a 17 km/h average wind speed [22], but reasonably comparable to the maximum spread rate of 2.3 m/min estimated for the Imizamu Yethu settlement fire [19], a far more complex fire spread situation which includes efforts to intervene and slow its progress.

Ignition can occur as a result of either direct flame impingement onto flammable material (cardboard or timber frames through gaps and vents; timber cladding; especially opposite vents and openings of adjacent structures), or by receiving sufficient radiation to exceed the critical heat flux of any of the materials present. Due to the large size of this experiment it is not possible to accurately measure behaviour at all positions, meaning that in some cases it is difficult to identify ignition mechanisms with absolute certainty. Photographic evidence (Figure 9) suggests that flame impingement was certainly present, and may well have been a dominant mechanism for fire spread in this experiment, although ignition by radiative exposure cannot be ruled out for all dwellings. The small dwelling spacings (< 2 m) common in these settlements provide ample opportunity for direct flame impingement to spread the fire from dwelling to dwelling, with the combination of large fuel loads and small, reasonably ventilated enclosures resulting in very quick development times from ignition through flashover into fully developed stages. As a result, fires can spread into multiple dwellings extremely quickly.

Predictions for a thermally-thick medium ignition model for timber suggest that even in the absence of direct flame impingement, heat flux values of around 25 kW/m<sup>2</sup> would result in ignition within less

than a minute [3], while the measured heat flux values around the recorded times of ignition are in excess of self-igniting heat flux values for most common household materials (8-20 kW/m<sup>2</sup> [5]). Although this suggests that radiation-induced self-ignition might be the dominant mechanism for fire spread, photographic evidence indicates that direct flame impingement was also present. Larger heat flux values likely represent direct flame impingement on the TSC disks, an observation which is confirmed for a number of the dwellings from the drone footage. Flame impingement is also supported by the observed spreading times, with no statistically significant difference in spreading rate between the 1.2 m and 2.2 m spaced dwellings visible in the overall results (Figure 8). Given the small time of spread and the proximity of dwellings, both mechanisms therefore contributed to the rapid spread observed. Dwelling spacing in typical dense informal settlements (1.0-1.5 m) are far smaller than the critical separation necessary to prevent rapid fire spread.

The observed temperature curves are consistent with the observations of Magnusson [23] for enclosures with intermediate ventilation factor values (0.07 in this case, see above). The mock dwellings in this experiment are initially well ventilated, before fires become marginally ventilation controlled and plateau around 1100°C. Of course, the uniform nature and distribution of the fuel load used in this experiment is only representative of household items in an average sense, and do not capture the effect items such as cooking oil, aerosol cans, and stored fuel would contribute [6].

It is possible that the importance of ventilation shows up as a larger-scale effect in the observed results: consider that dwelling C3 was surrounded by timber-clad dwellings on all four sides, and was the dwelling with the longest survival time. Intuitively it would be expected that C3 would experience intense fire exposure from the neighbouring timber structures and collapse rapidly. However, the intense burning of its timber-clad neighbours may have deprived its oxygen supply for a period, delaying the collapse of its timber frame structure. This hypothesis is supported by the ~350°C drop in the recorded ceiling temperature in C3 just as dwelling D3 goes into the flashover phase (green line in panel 3 of Figure 7).

Figure 5 presents the wind speed at the anemometer positions during the period of the experiment, presenting data both before and during the experiment. As would be expected in a real-life experiment the wind speed fluctuated continuously, with typical values between 10-20 km/hr, ~~and maximum or minimum values at~~with gusts reaching around 25 ~~and 5 km/hr respectively~~. Of great interest is the wind speed at the down-wind anemometer position, which is shown to increase at around 4 minutes into the experiment, when the first 16 homes had ignited, and continues until around 23 minutes after ignition, but less markedly towards the end. This apparent accelerating effect of the fire on average wind speed down-wind of the fire has in the past been associated with wildland fire [24, 25], and could possibly affect spread rates and ignition over longer distances through branding if intensified in a larger fire. Large conflagrations are known to modify wind conditions markedly [26, 27], so that this observation may reflect a similar effect at the lower end of the size scale. In such large fires branding becomes an important means of fire-spread, although~~However,~~ the spatial extent of the mock settlement used in ~~the present~~is experiment is not sufficient for the effect of branding be observed. Additional factors not accounted for in the experiment, such as topography and multi-storey structures, are also expected to affect the rate of fire spread and fire-wind interaction. This does highlight how in larger informal settlement fires, such as when hundreds of dwellings burn in a single disaster, it may be possible that fire phenomena associated with wildland fire behaviour may occur [28].

## 5 Conclusion

A full-scale fire spread experiment of a mock 20-dwelling mock settlement emphasises the critical hazard posed by the close proximity of dwellings in informal settlements. Combined with a mild wind in driving and directing the process, fire spread through the mock settlement within 5 minutes. The small dwelling spacings ( $< 2$  m) that are common in these settlements results in both direct flame impingement and radiation-induces auto ignition as the dominant mechanisms for fire spread from dwelling to dwelling, with the combination of large fuel loads and small, reasonably ventilated enclosures resulting in very quick development times from ignition through flashover into fully developed stages.

The results provide an initial set of observations against which event-based modelling of fire spread through informal settlements can be benchmarked and calibrated. However, factors resulting from human interaction with the fire, for example the effectiveness of firefighting efforts, and relocation of household items and furniture in response to an oncoming fire, will require a combination of fire dynamics and agent-based simulation techniques. Building on these observations, future experiments will be aimed specifically at (a) complicating factors such as branding, topography, multi-storey structures, and fluctuating wind, and at (b) developing potential measures of intervention that can delay the speed with which fire spread occurs.

On a macro-scale the fire spread is analogous to that observed in wildland fires, with the fire front moving progressively through combustible material. This behaviour would be aided if additional fuels were stacked between dwellings, as is often the case in real informal settlements where piles of tyres, rubbish, stored wooden pallets and broken equipment can be found. However, on an individual home level the distinct stages of enclosure fire development are recorded for dwellings. Hence, modelling of fire spread on global scale could range from between using simplified models with average spread rates defined by empirical terms that are a function of fuel type, home density, topography and wind. Alternatively, detailed computational fluid dynamics models, or one/two-zone models could be utilised to predict spread between individual dwellings, and such data used as sub-models within

global analyses considering each home individually. However, the challenge with all modelling techniques is that information about fuel load and settlement configuration is typically not known accurately, negating the potential to “accurately” calculate spread rates. Nevertheless, predictions about fire spread are still useful for potentially identifying how settlement layouts, construction types, fire safety interventions, and disaster preparedness may be improved.

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## Figure Captions:

Figure 1: Overall layout of the model settlement, also indicating instrumentation positions and positions where the experiment was initiated.

Figure 2: As-built structural drawings for dwelling frames and assembly, showing both timber-clad and galvanised sheeting-clad side panels. All dwellings had sheeting-clad roof panels. Also shown are the types of instrumentation modules and their positions on the dwelling walls.

Figure 3: (a) Thermocouples (TC) and thin-skin calorimeters (TSC) are fixed in position via modular instrumentation units pre-assembled using cold-formed steel conduits and fire-retarding blanket. Plastic wrapping was removed prior to the experiment. (b) Dwelling interior prior to burning, showing carboard linings and six timber cribs stacked from 48x48 mm 1.0 m lengths of South African pine.

Figure 4: Snapshots from overhead drone footage, starting from soon after ignition to just before the final dwelling collapse. Times are indicated relative to point of ignition.

Figure 5: Wind speed traces as recorded by the three anemometers, with time relative to the start of the fire. Note the decoupling of the windspeed down-wind from the fire to the up-wind and far-field traces as the fire reaches full intensity.

Figure 6: Summary of timeline for the experiment. Dashed line indicates timeline based only on video footage, where the thermocouples fitted to the ceiling malfunctioned.

Figure 7: Average ceiling temperatures inside each dwelling, clearly illustrating how down-wind ignition follows shortly after flashover of a given dwelling.

Figure 8: (a-c) Frequency distributions of time between salient events during the burning of individual dwellings and fire spread to down-wind neighbours. (d) Comparison of time lag between temperature

traces (represented by time between end of flashover events) for different separation distances, with error bars representing one standard deviation.

Figure 9: Photographic evidence documenting fire spread by direct flame impingement (FI), flame lengths out of dwelling vents (FL), and flame heights above roof level (FH), with 4 m tall instrument units (IU) pointed out for reference. Where times are not obtainable from the source footage, it is estimated based on correlation to other footage, and indicated as approximate (indicated with ~).

Figure 10: Heat flux recorded across a 2.2 m distance separating the 4-instrument units on dwellings C1 and C2, facing dwellings B1 and B2, respectively.

Figure 11: Heat flux recorded across a 1.2 m distance separating the 2-instrument units on dwellings B2, B3, C3, and D2, facing dwellings A2, A3, B3, and C2, respectively.

Figure 12: Heat flux onto side panels, as labelled in Figure 1. High heat flux values on B0 correspond to direct flame impingement.

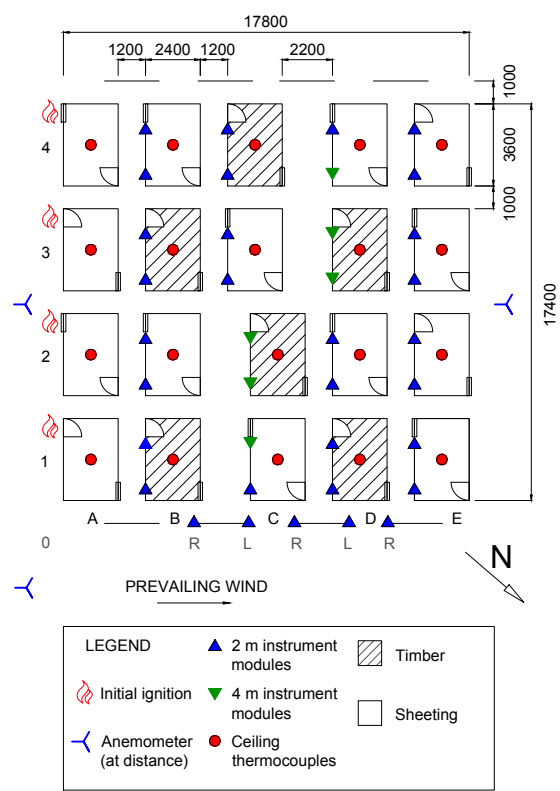


Figure 1: Overall layout of the model settlement, also indicating instrumentation positions and positions where the experiment was initiated.

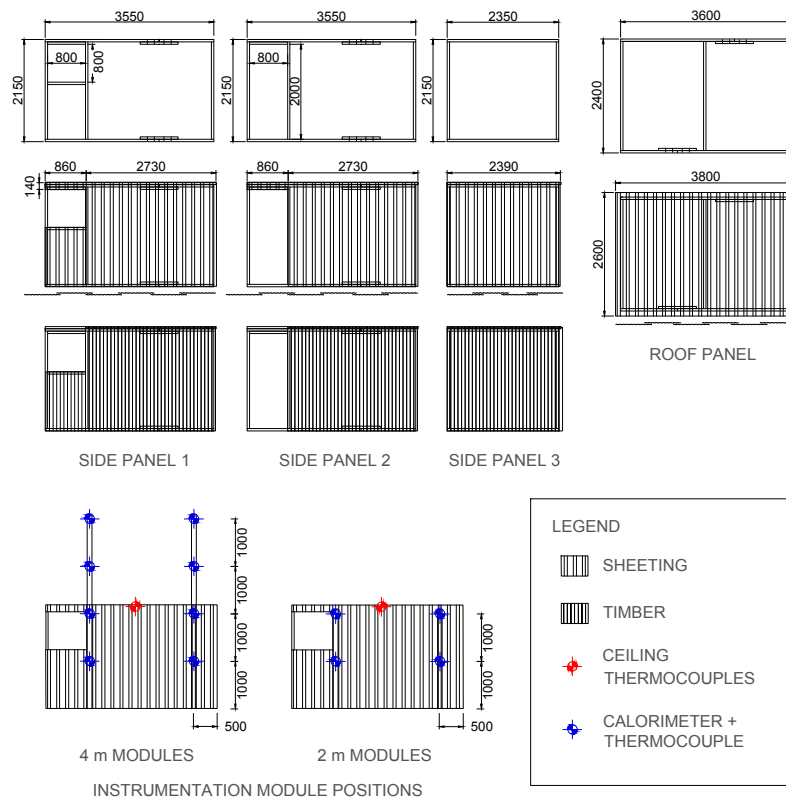


Figure 2: As-built structural drawings for dwelling frames and assembly, showing both timber-clad and galvanised sheeting-clad side panels. All dwellings had sheeting-clad roof panels. Also shown are the types of instrumentation modules and their positions on the dwelling walls.



(a)



(b)

Figure 3: (a) Thermocouples and thin-skin calorimeters (white disks) are fixed in position via modular instrumentation units pre-assembled using cold-formed steel conduits and fire-retarding blanket. Plastic wrapping was removed prior to the experiment. (b) Dwelling interior prior to burning, showing cardboard linings and six timber cribs stacked from 48x48 mm 1.0 m lengths of South African pine.





Figure 4: Snapshots from overhead drone footage, starting from soon after ignition to just before the final dwelling collapse. Times are indicated relative to point of ignition.

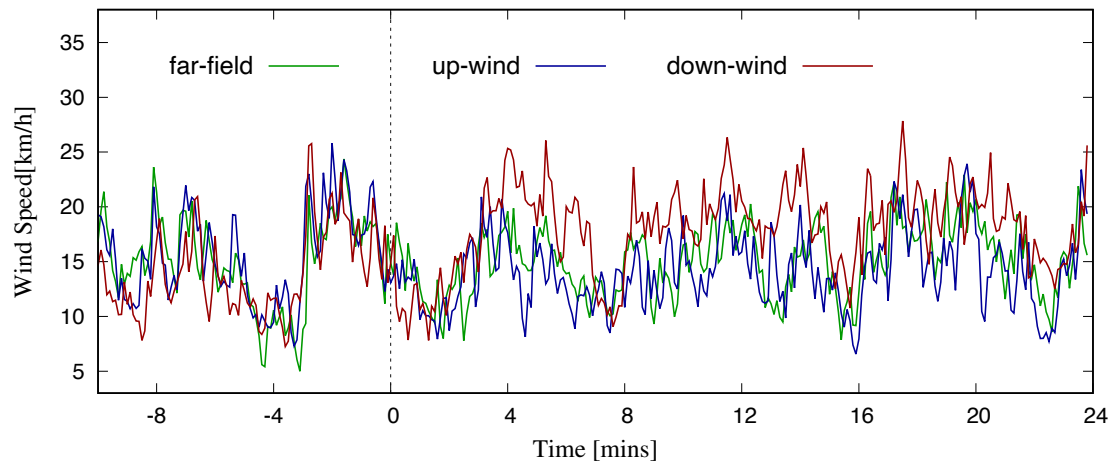


Figure 5: Wind speed traces as recorded by the three anemometers, with time relative to the start of the fire. Note the decoupling of the windspeed down-wind from the fire to the up-wind and far-field traces as the fire reaches full intensity.



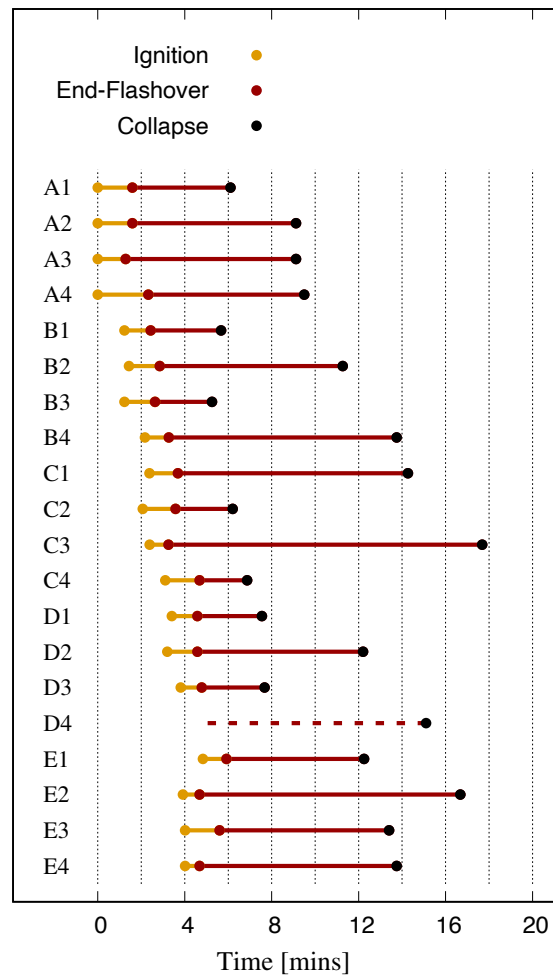


Figure 6: Summary of timeline for the experiment. Dashed line indicates timeline based only on video footage, where the thermocouples fitted to the ceiling malfunctioned.

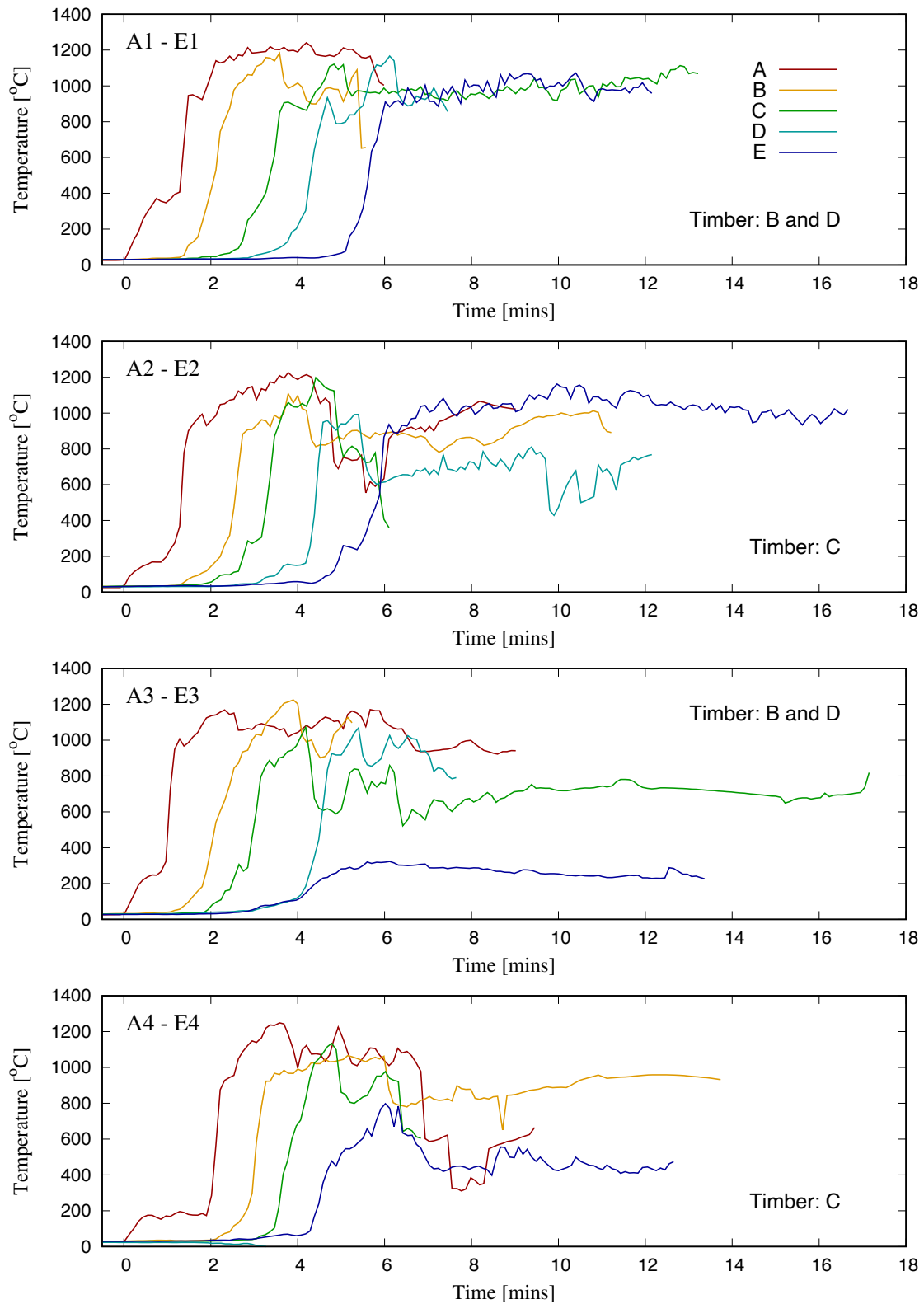


Figure 7: Average ceiling temperatures inside each dwelling, clearly illustrating how down-wind ignition follows shortly after flashover of a given dwelling.

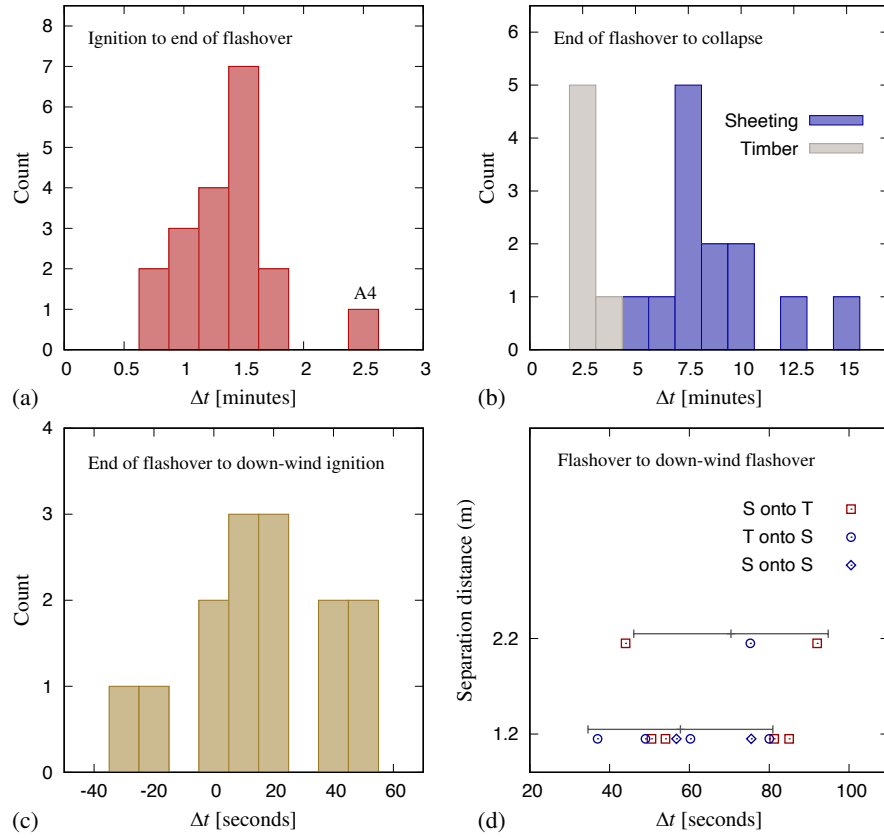


Figure 8: (a-c) Frequency distributions of time between salient events during the burning of individual dwellings and fire spread to down-wind neighbours. (d) Comparison of time lag between temperature traces (represented by time between end of flashover events) for different separation distances, with error bars representing one standard deviation.



Figure 9: Photographic evidence documenting fire spread by direct flame impingement (FI), flame lengths out of dwelling vents (FL), and flame heights above roof level (FH), with 4 m tall instrument units (IU) pointed out for reference. Where times are not obtainable from the source footage, it is estimated based on correlation to other footage, and indicated as approximate (indicated with ~).

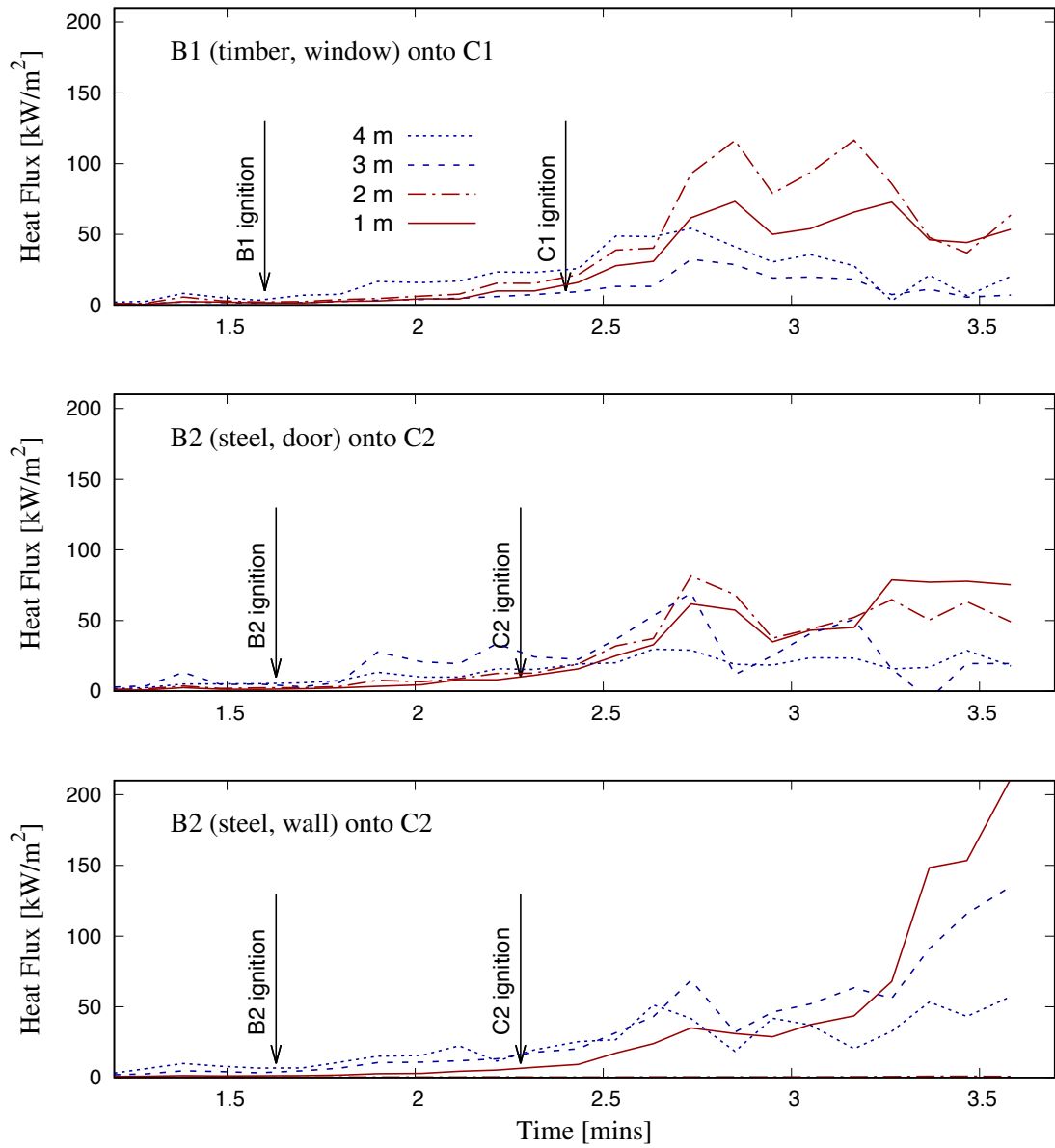


Figure 10: Heat flux recorded across a 2.2 m distance separating the 4-instrument units on dwellings C1 and C2, facing dwellings B1 and B2, respectively.

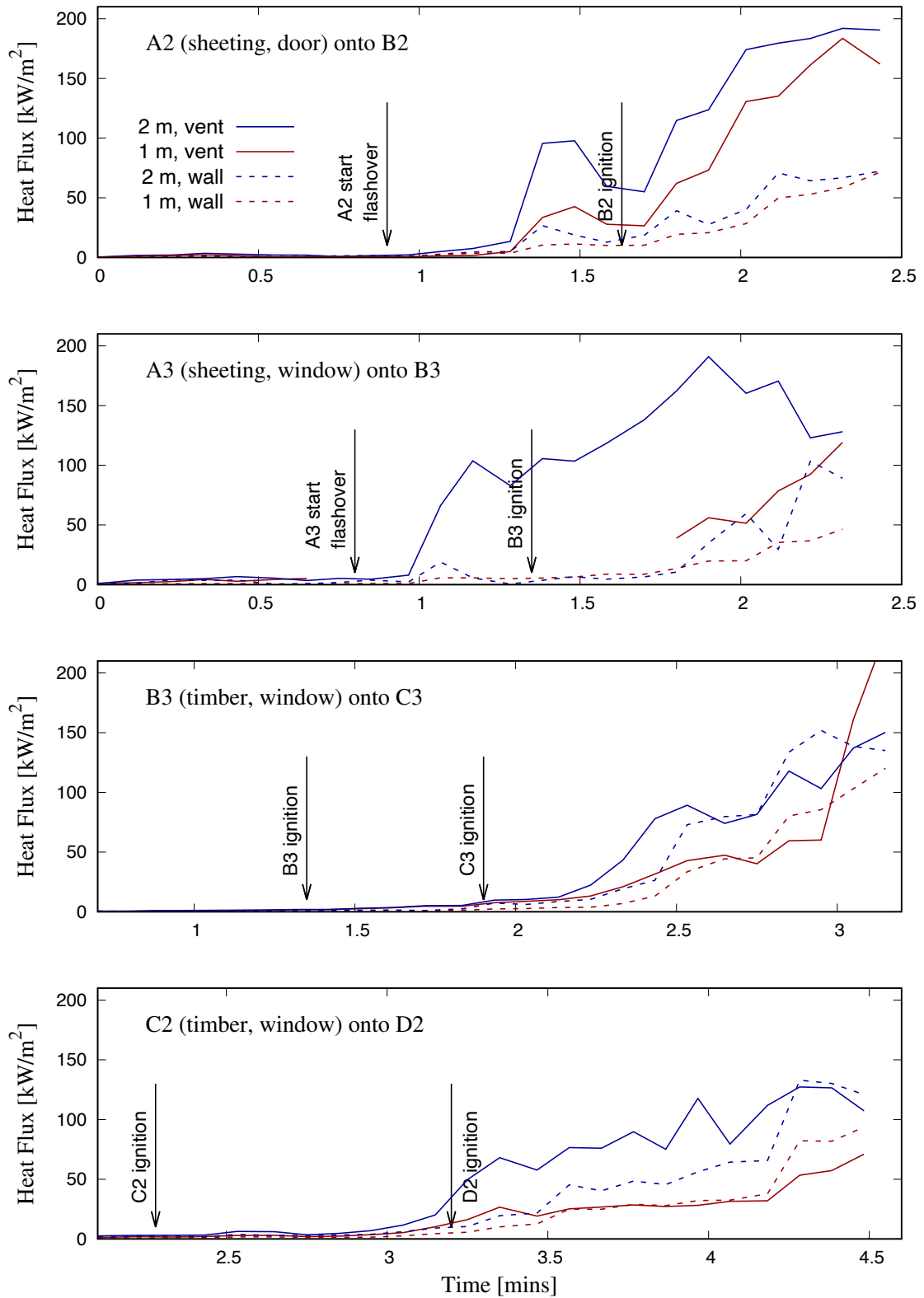


Figure 11: Heat flux recorded across a 1.2 m distance separating the 2-instrument units on dwellings B2, B3, C3, and D2, facing dwellings A2, A3, B3, and C2, respectively.

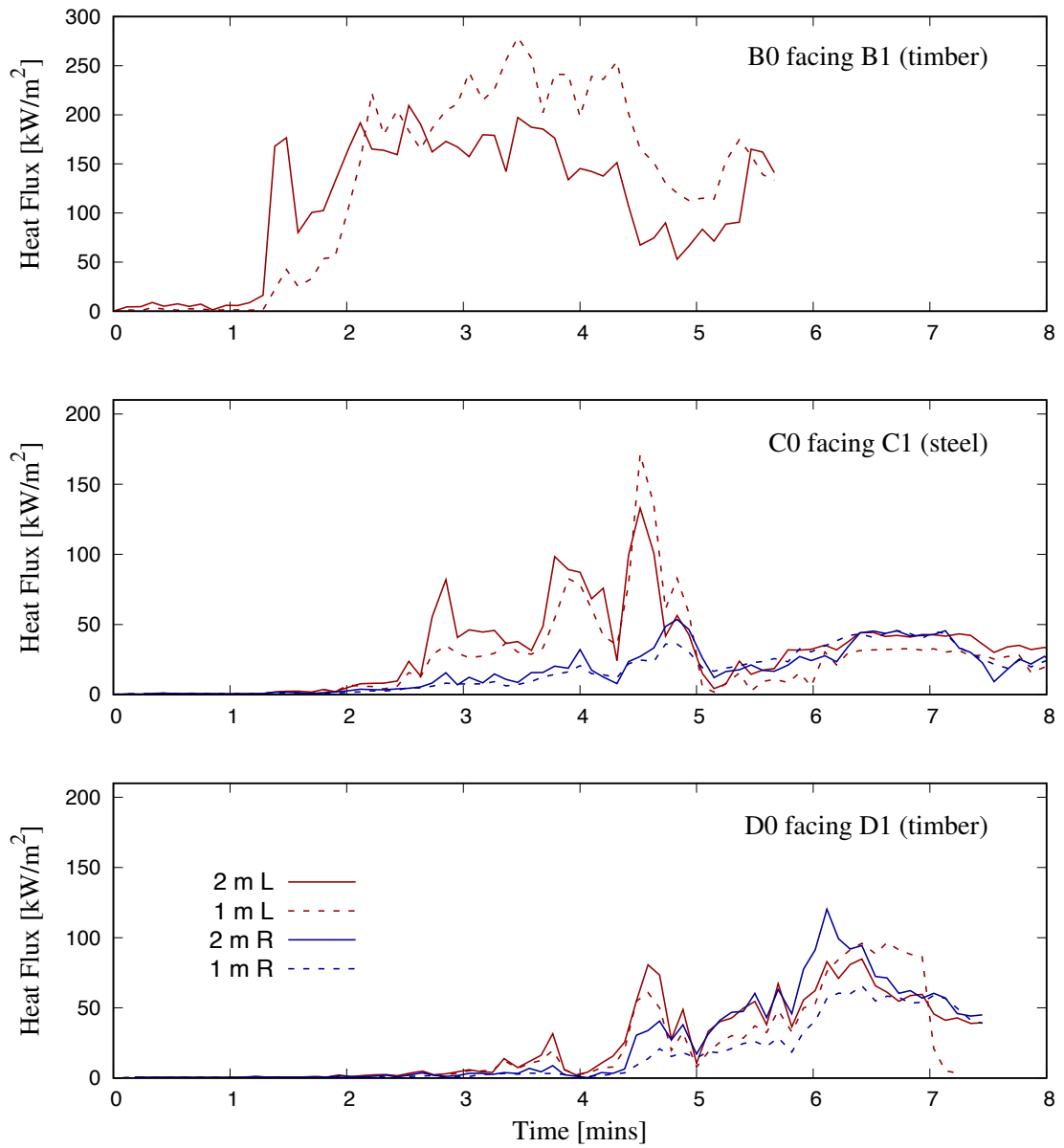


Figure 12: Heat flux onto side panels, as labelled in Figure 1. High heat flux values on B0 correspond to direct flame impingement.